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The application of AIRS radiances in numerical weather prediction

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Introduction

In 2002, the Atmospheric Infrared Sounder (AIRS) (Aumann et al. 2003) was launched on AQUA the second of the EOS polar-orbiting satellites. The AIRS was the first of a new generation of meteorological advanced sounders able to provide hyperspectral data for operational and research use. A large investment has been made internationally to upgrade the meteorological satellite systems to carry these advanced instruments. The US Cross-track Infrared Sounder (CrIS) and Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS), as well as the European Infrared Atmospheric Sounding Interferometer (IASI) represent significant investment in these systems. As a result, demonstration of the benefit of hyperspectral data on numerical weather prediction (NWP) has been a high priority. Observing system experiments designed to examine effective methods to use AIRS hyperspectral radiances are summarised here. The first experiments to use full spatial resolution hyperspectral radiance data, available in real time from the AIRS instrument are reviewed. The result of these assimilation trials was significant improvements in forecast skill, compared to the global system without AIRS data over both the northern and southern hemispheres. In addition, an experiment is described which showed the advantage of using all AIRS fields of view in analysis as opposed to the use of sampled fields of view (typically one-in-eighteen) often used for NWP. Experiments showing the impact of using hyperspectral data of different spectral coverage are also described, and show the importance of careful selection of instrument channels for assimilation. Overall, the results indicate the significant benefits to be derived from AIRS data assimilation and the benefits to be gained from an enhanced use of the information content contained in the AIRS radiance observations.

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Background

After the launch of the AIRS in 2002 and the six-month calibration period the AIRS was able to provide operational data. The improved spectral resolution it provided has led to a significant increase in vertical resolution and accuracy in determining thermal and moisture fields and increased accuracy in determination of the concentrations of absorbers such as ozone. The methods used to provide improvements in NWP from the use of radiance observations taken by this instrument are documented in the impact studies below.

Data assimilation studies

In mid-2004 the Joint Center for Satellite Data Assimilation (JCSDA) demonstrated significant impact from AIRS data in both the northern and southern hemispheres (Le Marshall 2005a,b). This was achieved through use of an enhanced spatial and spectral AIRS observational dataset in conjunction with an analysis methodology that paid additional attention to the possible presence of clouds. Experiments demonstrating the benefits of AIRS data assimilation and the contribution of enhanced spatial and spectral resolution data are described below.

Assimilation of full spatial resolution (all footprints) AIRS data

To examine the impact of adding full spatial resolution AIRS radiance observations to the National Centers for Environmental Prediction (NCEP) operational database (without AIRS), the NCEP operational T254 64-level version of the GFS (November 2004 version) was employed. All channels for all fields of view (fovs) from the AIRS instrument on the AQUA satellite were processed into the current BUFR format. This provided 281 channels of AIRS data at each footprint of which 251 were suitable for assimilation. These particular channels describe most of the variance of the 2,378 AIRS channels (Susskind et al. 2003). The NCEP operational global analysis and prognosis system (GFS) (Derber and Wu 1998; Derber et al. 2003) using the full operational database, available within real-time cut-off constraints and without AIRS data, was employed as the control ('Ops'). The database included all available conventional data and the satellite data listed in Table1. The radiances from the AQUA Advanced Microwave Sounding Unit-A (AMSU-A) instrument were not included in the control or experimental database. Radiative transfer calculations were performed using the JCSDA Community Radiative Transfer Model (CRTM), (Kleespies et al. 2004) The experimental system also employed the GFS with the full operational database (i.e. the control database) plus full spatial resolution AIRS radiance data ('Ops + AIRS'), available within operational time constraints.

The global analysis was modified to include the use of these AIRS data and the experimental system designed to determine the impact on real-time operations of the hyperspectral AIRS radiance data.

The analysis methodology is described in Le Marshall et al. (2005a,b). In a typical six-hour global assimilation cycle approximately 200 million AIRS radiances (i.e. 200×10^6 / 281 fields of view), were input to the analysis system. From these data about 2,100,000 radiances (281 radiances (channels) in approximately 7450 analysis boxes) were selected for possible use, and result in about 850,000 radiances free of cloud effects being used in the analysis process. That is effective use is made of approximately 41 per cent of the data selected for possible use. The data volumes are summarised in Table 2.

Assimilation of full and reduced spatial Resolution AIRS data

In order to examine the importance of using the full spatial resolution AIRS data as opposed to the one in eighteen fields of view often used for NWP, results from another data assimilation experiment for August-September 2004 have been recorded. In this study, forecasts which used radiances from the currently available thin (one-in-eighteen fovs) real-time AIRS dataset in addition to the full operational database ('Cntl AIRS'), have been compared to results from the use of a full spatial resolution (Spatially Enhanced, all footprints-'SpEn AIRS') AIRS dataset in addition to the operational database. In these cases the operational database included AQUA AMSU-A. The trial again used the NCEP operational T254, 64 level GFS (November 2004 version).

Assimilation of full and reduced spectral coverage

The full NCEP operational database including AQUA AMSU-A for the period 2 January to 15 February 2004 has been used to provide a series of control analyses and forecasts from the operational NCEP operational T254 64 level GFS (June 2005 version).

The analyses and forecasts have been repeated using the full operational database plus full spatial resolution AIRS observations from the 115 AIRS channels whose central wavelength is between 3.7 and 9.3 μm ('short AIRS'). In a third series of analyses and forecasts, the full operational database has been used with 152 channels of AIRS data i.e. full spatial resolution, including 152 of the 281 channels currently available for real-time NWP covering the

Table 1. The satellite data used by the control forecasts.

HIRS sounder radiances	TRMM precipitation rates
AMSU-A sounder radiances	ERS-2 ocean surface wind vectors
AMSU-B sounder radiances	Quikscat ocean surface wind vectors
GOES sounder radiances	AVHRR SST
GOES, Meteosat atmospheric motion vectors	AVHRR vegetation fraction
	AVHRR surface type
GOES precipitation rate	Multi-satellite snow cover
SSM/I ocean surface wind speeds	Multi-satellite sea-ice
SSM/I precipitation rates	SBUV/2 ozone profile and total ozone

Table 2. AIRS data usage per analysis cycle.

Total data input to analysis	~200×10^6 radiances
Data selected for possible use	~2.1×10^6 radiances
Data used in 3D VAR analysis (clear radiances)	~0.85×10^6 radiances

full spectral range 3.7-15.4 μm ('airs – 152ch'). In a fourth series of analyses and forecasts, the full operational database has been used with all (251 channels) of AIRS data ('airs – 251ch') i.e. full spatial resolution, including 251 of the current 281 channels available for real-time NWP covering the full spectral range 3.7-15.4 μm.

Data assimilation results

Full spatial resolution (all footprints) AIRS data

In the impact studies using full spatial resolution AIRS data with the NCEP GFS, cloud free AIRS radiance data were identified and used, by the methods described previously. The verification statistics were derived using the NCEP operational verification scheme.

A summary of the results is seen in Figs 1 and 2. Figure 1 shows the geopotential height anomaly correlations (AC) for the GFS at 500 hPa over the southern hemisphere for January 2004 at one to five days, with and without AIRS data. It is clear the AIRS data have had a beneficial effect on forecast skill over the southern hemisphere during this period. Figure 2 shows the 500 hPa AC over the northern hemisphere for January 2004. The results again show improved forecast skill.

During a similar series of impact studies using full spatial resolution AIRS data, an examination was undertaken of the moisture field in the lower troposphere. An example of the forecast impact is seen in Fig. 3 where forecast impact evaluates which forecast (with or without AIRS) is closer to the analysis valid at the same time.

$$Forecast\ Impact = 100\ (Err_{Cntl} - Err_{AIRS})\ /Err_{Cntl}$$

Fig. 1 **500 hPa Z anomaly correlations for the GFS with (Ops.+AIRS) and without (Ops.) AIRS data, southern hemisphere, January 2004.**

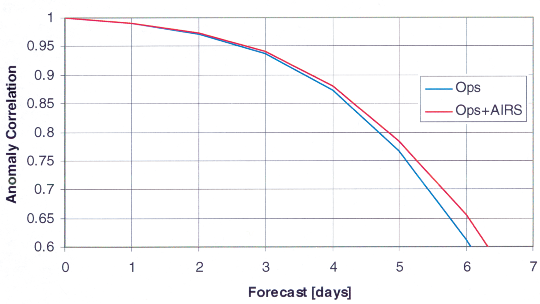


Fig. 2 **500hPa Z anomaly correlations for the GFS with (Ops.+AIRS) and without (Ops.) AIRS data, northern hemisphere, January 2004.**

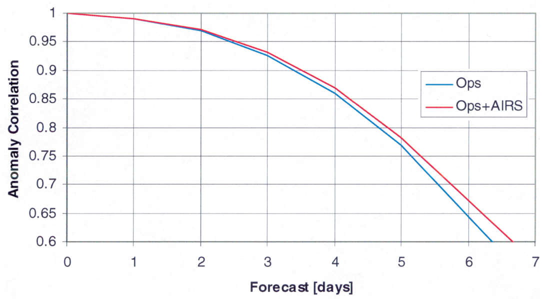
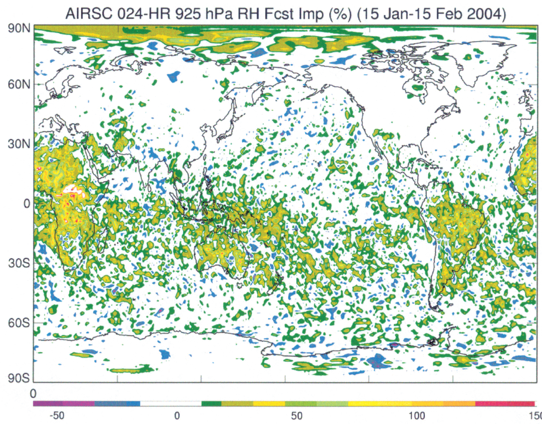


Fig. 3 **Forecast impact improvement/degradation (%) of the 12 h relative humidity forecast at 925 hPa.**



where Err_{Cntl} is the error in the control forecast. Err_{AIRS} is the error in the AIRS forecast. Dividing by the error in the control forecast and multiplying by 100 normalises the results and provides a per cent improvement or degradation. A positive forecast impact means the forecast is better with AIRS data included. Figure 3 shows a degree of improvement over a significant area in the 925 hPa relative humidity in the twelve-hour forecast with AIRS. Significant areas of improvement were also seen in the 850 hPa relative humidity and the total precipitable water at twelve hours.

Full and reduced spatial resolution AIRS data

In an experiment to examine the importance of using the full spatial resolution AIRS data as opposed to the one-in-eighteen fields of view often used in NWP, results for an assimilation experiment over August and September 2004 are provided. In this study, forecasts that used radiances from the currently available thinned (one-in-eighteen fovs) real-time AIRS dataset in addition to the operational database were compared to results from the use of a full spatial resolution (thick) dataset in addition to the operational database. In these cases the operational database included AQUA AMSU-A (see Fig. 4). Identical versions of the GFS were used in both cases. It is clear that the increased information related to atmospheric temperature and moisture contained in the (thick) full spatial density dataset has resulted in improved analyses and forecasts.

Full and reduced spectral coverage

Figure 5 shows the results from a comparison of forecasts: (a) the control (full operational database, including AQUA/ AMSU-A); (b) using the full operational database plus full spatial resolution AIRS observations from the 115 AIRS channels whose central wavelength is between 3.7 and 9.3 μm ('short AIRS'); (c) a third series of analyses, where the full operational database has been used with 152 AIRS channels (central wavelengths 3.7 to 15.4 μm) of AIRS data, 'AIRS-152ch' (i.e. full spatial resolution, including 152 of the 281 channels currently available for real-time NWP, a subset presently used for operational NWP); and (d) a series of analyses and forecasts, where the full operational database has been used with all (251 channels, central wavelengths 3.7 to 15.4 μm) AIRS data, 'AIRS-251ch' (i.e. full spatial resolution, including 251 of the 281 channels currently available for real-time NWP).

Figure 5 shows the 1000 hPa and 500 hPa geopotential height (Z) five-day forecast anomaly correlations for the northern and southern hemispheres. It was apparent in this trial that addition of the short wave channels ('short AIRS') to the operational observation database generally provided a positive increment at five days with a larger improvement being seen in the southern hemisphere 1000 hPa fields. It was also clear for this period that addition of long wave channels (whose central wavelength is greater than 9.3μm, 'airs-152ch', 'airs- 251ch') generally provided improved forecasts in each of the categories. The clear advantage from using the full spectral range with 251 channels of AIRS data was also apparent in the experiments for this period.

Fig. 4 500 hPa Z anomaly correlations for the GFS with current thinned – one AIRS fov in 18 (Cntl AIRS) and for the GFS using all AIRS fovs (SpEn AIRS), northern hemisphere, August/September 2004.

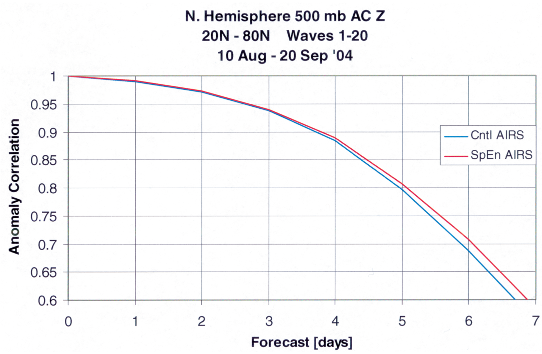
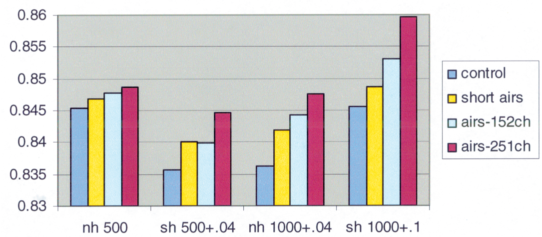


Fig. 5 1000 and 500 hPa Z anomaly correlations for the GFS for the control, short (using 115 AIRS short wave channels), airs-152ch using 152 out of the 281 channels available for real-time NWP and airs-251ch using 251 out of the 281 channels available for real-time NWP, northern and southern hemisphere, January/ February 2004.



Conclusions

The introduction of AIRS hyperspectral data into environmental prognosis centres was anticipated to provide improvements in forecast skill. Here we have noted results where AIRS hyperspectral data, used within stringent operational constraints, have shown significant positive impact in forecast skill over both the northern and southern hemisphere for January 2004. The magnitude of the improvement is quite significant and would normally take several years to achieve at an operational weather centre. We have also noted the improvement gained from using AIRS at a spatial density greater than that used generally for operational NWP. In addition we have completed some studies to look at the impact of spectral coverage and found for the period studied, use of a fuller AIRS spectral coverage and the full AIRS spectral range, namely 3.7 to 15.4 μm, provided superior forecasts.

In conclusion, given the opportunities for future enhancement of the assimilation system and the resolution of the hyperspectral database, the results indicate a considerable opportunity to improve current analysis and forecast systems through the application of hyperspectral data. It is anticipated current results will be further enhanced through use of higher spectral and spatial resolution data. Further improvements may also be anticipated through use of cloudy data and the use of complementary data such as Moderate Resolution Imaging Spectroradiometer (MODIS) radiances for determining cloud characteristics. Improvements are also expected from the effective exploitation of the new hyperspectral data that will become available from the IASI, CrIS and geostationary instruments such as the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS).

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